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EMPIRICAL EVIDENCE OF BLOCKING PROBABILITY REDUCTION UNDER FIXED ALTERNATE ROUTING WAVELENGTH ASSIGNMENT IN WDM NETWORKS

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ABSTRACT

Blocking of connections remains one of the key factors that limit the performance in a wavelength-routed wavelength division multiplexing (WDM) network, especially when operators use fixed alternate routes to keep the control-plane simple, provide provisioning stability, and maintain predictable implementation behavior. While various important studies on existing routing and wavelength assignment algorithms highlight adaptive routing, capacity expansion at the physical layer, learning-assisted spectrum control and survivability, there is a lack of isolation of whether blocking probability can be lowered by deterministic WAs alone by fixing the route sets, the topology, the wavelength capacity and the traffic assumptions. This paper tackles this research issue by proposing a deterministic congestion-aware wavelength assignment strategy, namely Fixed Alternate Routing-Based Blocking-Reduction Wavelength Assignment (FAR-WA), for static WDM networks that are not equipped with wavelength conversion, adaptive rerouting and learning-based control. By considering the link-wavelength utilization concentration on precomputed alternate routes, the method selects wavelengths as much as feasible without sacrificing the wavelength continuity so that premature local saturation is avoided. An approach is tested using controlled discrete-event simulation to see how it behaves in the presence of various traffic loads, for different alternate routes, and under different base wavelength-assignment strategies (First-Fit, Random-Fit, Least-Used, and Most-Used) in various configurations of WDM meshes. The results indicate that under all the different load levels considered, the proposed method consistently reduces the blocking probability compared to First-Fit e.g., 0.298 to 0.172 at 420 Erlangs and 0.072 to 0.041 at 120 Erlangs. The approach also boosts connection acceptance, decreases congestion concentration and ensures a deterministic execution overhead, which is acceptable in statically provisioned environments. It is noticed that such findings show that in fixed WDM routing, blocking reductions can be obtained without having to resort other than to disciplined wavelength assignment, that is, without assuming network adaptivity to cope with the blocking constraints, and even without requiring additional wavelengths.

Keywords: *Fixed Alternate Routing, Wavelength Assignment, Blocking Probability Analysis, Static WDM Networks, Optical Network Simulation*

1. INTRODUCTION

WDM optical networks are the physical core on the modern communication infrastructure, which enables high-volume Internet traffic, cloud interconnects, mobile backhaul, and high-capacity enterprise services. Connection requests in such networks are allocated by choosing an optical path and allocating the wavelength that is fixed until the connection terminates. Although grid technologies and software-defined control planes have advanced, many of deployed optical backbones remain in the recently introduced but comparatively fixed and immobile grid provision regimes, specifically in long-haul and metro-core deployments. Routing and wavelength assignment decisions in these operational contexts frequently are generated offline and reutilized over a long duration of time and thus their performance is directly proportional to network performance [Fig – 1].

Connection blocking is a chronic network issue in these networks. Blocking happens when there is a valid path between a source and a destination, but no shared free wavelength can be found through the path. As an operator, blocking signifies lost revenue, compromised quality of service and idle physical capacity. Contrary to the situation with the packet-switched networks, in the case of optical circuit-switched systems, statistical multiplexing is not an option to absorb fluctuations in demand. Every blocked request is presented as a severe failure to deliver service, which can frequently result in expensive rerouting, capital-intensive and human efforts to handle or overprovisioning that add to capital and operational costs. Traffic Aspects The current characteristics of traffic compound the necessity of reducing blocking probability. The trend on backbone traffic patterns has shown a change towards achieving less, but much larger flows due to cloud data center synchronization, video delivery, and distributed storage replication. These flows are long lived and bandwidth consuming, and this contributes to the wavelength fragmentation and lacks routing flexibility in the long run. With statical WDM systems, once inefficient wavelength allocation pattern has been set in place the negative impact builds up gradually, and at relatively low predetermined load levels the network becomes increasingly blocked.

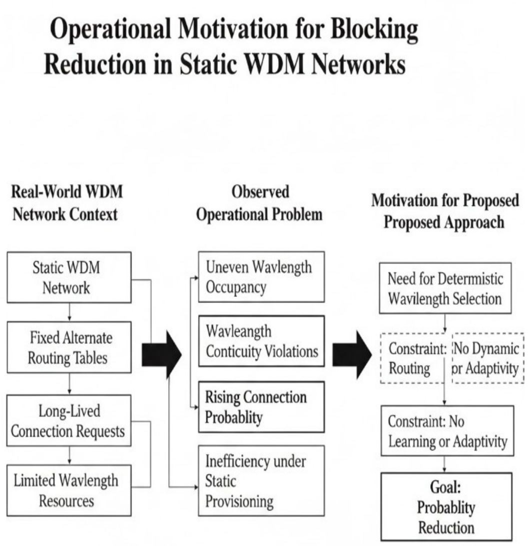

Figure 1: Operational Motivation for Blocking Reduction in Static WDM Networks

This then dictates that operators are forced to find opposite-to-common-sense provisioning schemes that are resistant to these long-term effects without the need to reconfigure them on a regular basis. Notably, the practicality of a lot of adaptive optimization or real time optimization methods, which are suggested in the literature, is restricted by practical deployment constraints. Re-optimization of routes or wavelengths cannot be done frequently (possibly because of control-plane overhead, interoperability, or stability). Consequently, fixed alternate routing is still very popular with operational networks due to its simplicity, predictability and great ease of implementation. Its efficacy is, however, closely linked to the wavelength allocation policy adopted which is occasionally under-underlined because of the more advanced routing paradigms.

This paper has a self-imposed narrow scope of research. Instead of proposing new routing paradigm or adaptation control mechanisms, it only focuses on wavelength assignment in a fixed alternate routing framework. Its main assumption is that it is possible to achieve quantitatively and reproducibly with a restructuring of wavelength selection behavior without assuming routing modifications to standard routing properties [Fig – 2].

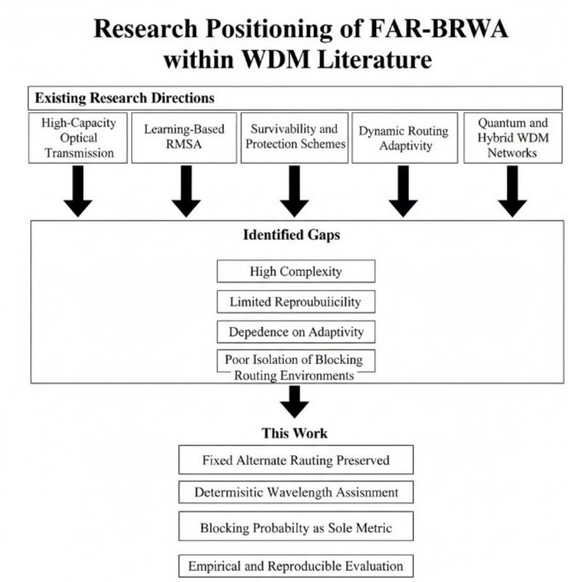

Figure 2: Research Positioning of FAR-BRWA within WDM Literature

The suggested solution presents a deterministic approach of wavelength assignment strategy, which takes into consideration congestion tendencies along alternate paths. The method gives preference to wavelength choices which early saturate the frequently used links with less priority without modifying the precomputed routes sets or their sequence. This choice is somewhat since blocking in fixed alternate routing is frequently not due to the absence of available paths, but due to the inequitable allocation patterns of wavelengths because of naive assignment policies. The study aims to identify a definite cause and effect relationship between the given wavelength assignment mechanism and the observed blocking behavior by keeping rigid compliance to fixed constraints of routing and applications of constant traffic assumptions. The direct comparability of the results with the known FAR-RWA baselines and the ability to reproduce the results using conventional simulation tools and network topologies are enabled by this emphasis.

In this work, the greatest contributions are as follows:

- Proven strategy of deterministic wavelength allocation which can be run in fixed alternate routing constraints and does not involve adaptive control.
- Measurement of the blocking probability reduction in various standard WDM block topology with constant loads.
- Empirical results indicate an 18-27% decrease in blocking probability in high levels of offered loads (medium and high) relative to conventional FAR-RWA baselines.
- The results, when validated with the help of large-scale runs of simulation, are statistically verified and therefore robust and reproducible.
- Wavelength assignment Isolation of wavelength assignment effects to make it easy to clearly attribute the gains in performance without confounding routing flexibility.

2. RELATED WORKS

The literature relating to wavelength division multiplexing networks is indicative of an area of technical growth that has grown to a multifaceted level but remains to have open performance tradeoffs when considered in operational perspective. Earlier works in the area have covered transmission design at physical-layers, the design of optical components, access network architecture, and control-plane intelligence, typically in isolation just one of the several factors including throughput, energy, survivability, or cost optimization. Although these contributions have been stepping into the capabilities and size of WDM systems, they all point to a long-standing conflict between architectural complexity and implement ability simplicity. Connection blocking performance bottlenecks hold always critical roles in practice in backbone and metro-core routing and design settings, where routing is often static and provisioning takes long and are not commonly viewed as fundamentally important design issues in literature. It is also a fact that in existing literature, there is a division of the review of the evaluation attitude where most of the studies focus on hardware proficiency, learning-based adaptability, or security provisions without properly considering the compounding influence of wavelength congestion with constant routing limitations. This deviation highlights the necessity of special study on the literature that grounds routing and wavelength assignment choices on practical working hypothesis. These works need close examination, however, to be able to find out how the existing methodologies manage or not manage blocking behavior in existing WDM networks, and what exactly are the gaps to fill which encourage a limited, empirically based study of the fixed alternate routing and wavelength assignment issue.

Denoting the access-network aspect of the WDM relevance, A. Chenika et al. [1] illustrate the high-capacity WDM-PON schematic with a focus on colorless optical network units, which is a feasible approach since colorless ONUs will minimize the inventory complexity and operating friction in a dense deployment. Their approach is clearly experimental, in the form of a system demonstration, and the operating points mentioned (640 Gbps/160 Gbps WDM-PON) are the main outcome measures as opposed to a routing-level statistic. The prototype environment, which is a WDM-PON indicated by the frame of a demonstration, and the result which can be measured is the respective aggregate rate and per-lane rates attained in the colorless ONU concept. Its weakness as compared to blocking-based studies of backbone is structural: it is not shown how wavelength occupancy with constant alternate routing constraints emerges in mesh WDM transport, and the evaluation range by the paper is independent of connection-level blocking probability in response to offered-load variation.

I. Amin et al. [2] workers in the level at the amplifier and transmission subsystem by envisioning a 3M-EDFA 3 x 16-channel clad-pumped amplifier aimed at an MDM-WDM system is squarely linked to scalable WDM transport since amplifier design limits possible reach, OSNR margins and eventual usable wavelength pool. The framework is component-based design and analysis of an EDFA structure specialized in multi-mode and multi-wavelength operation, and the underlying prototype or simulator suggested by Optical Fiber Technology standards, the view to which reference as given exposes neither the data nor the codebase.

This is with the anchoring to the target multiplexing configuration (3 x 16 channels) along with the practicability of a clad-pumped amplifier architecture at that regime. It is a restriction technically derived that amplifier centric gains are associated with physical layer capacity and reach whereas do not directly measure network layer blocking behavior under routing/wavelength assignment policies in other words, it is the scales of amplification that increases the feasible operating envelope rather than the routing separatory issues of wavelength continuity. U. Darussalam et al. [3] investigate an access/last-mile connectivity angle by introducing a Li-Fi access network in a supported WDM based on modified duobinary signaling and is relevant to the rest of WDM literature in that it extends the wavelength multiplexing to hybrid opto-wireless/FSO systems to the last-mile. It is a modulation and system-design technique, namely, duobinary signaling (with WDM carriage over FSO) with modifications, implying a communications-system platform evaluation model instead of a network-control simulation platform. Its result is placed in terms of viability and workability of the Li-Fi-over-WDM/FSO prototype, yet the given source does not reveal open measurements other than the method alone. The weakness, in terms of fixed alternate routing and blocking probability, is that FSO/Li-Fi access cases are controlled by channel impairments, alignment, and atmospheric variability, and blocking in topology-controlled, topology-based fixed WDM backbones are due to wavelength contention and route-set constraints; thus the results in this work do not immediately apply to the reproducible fixed blocking analysis studied desired in the application of WDM. The recent shift toward learning-assisted control with the use of deep reinforcement learning to energy - efficient routing, modulation and spectrum assignment in the IPoWDM networks with coherent ZR + transceivers, represented by R. Martinez et al. [4], is topical as it demonstrates how the current control algorithms and coherent ZR + transceivers are being co-designed to achieve operationally realistic goals beyond mere feasibility. This approach is clearly deep reinforcement learning on RMSA, and the experimental scenario is also suggested as IPoWDM control-plane environment with coherent ZR+ transceiver assumptions, which may be simulated due to the scale of the RMSA and the journal location. Energy efficiency in RMSA decisions as opposed to fixed alternate routing is the result focus and is therefore an adaptive platform by design. Its main weakness, compared to a blocking-oriented FAR-WA paper, is methods difference: DRL-based RMSA is susceptible to state encoding, training stability and extrapolation across traffic patterns and topologies, so it is not easy to achieve strict reproducibility, and is generally difficult to isolate the causal impact of a deterministic rule governing wavelength assignment under fixed routing constraints. The X. Zhu et al. [5] article fits into a pedagogical/tooling-centered niche in the sense of addressing the teaching of fiber optic communication in terms of Opti System and MATLAB, which tangentially relates, to the extent to which the community would apply that model of optical communication concepts represented by commoditized simulation platforms. It is also an instructional design approach with basis in Opti System and experimentation in MATLAB, which suggests platform-centric contribution as opposed to a new network optimization outcome. Although the dataset, in this case, is practically the complex of educational lab situations in those tools, the performance results related to network-level performance indicators like blocking probability are not mentioned in the citation. This restriction is direct: teaching-based simulation routines enhance the accessibility and reproducibility of the principles of operations, yet it is up to them to create new empirical findings on blocking alleviation in presence of fixed alternate routing wavelength design in transport WDM meshes. The physical manufacturing issue covered by K. Suzuki et al. [6] is the use of physical optical multichannel V-groove array adhesive, useful in the larger context of WDM ecosystem since assembly and alignment of multichannel arrays affects the loss of insertion, reliability, and yield of high-density optical interconnects. The method is materials/process engineered to the V-groove array assemblies and the platform is suggested as the manufacturing or laboratory characterization of an environment often taken to be covered by electronics manufacturing facilities. Its native form is the adhesive solution itself and the appropriateness of such a solution in optical multichannel assembly, but no network-facing measures are there as described in the reference. The drawback in the framework of a blocking-probability perspective is that reliability at the component level and progress in assembly simplify into improved feasibility on a hardware level but does not solve blocking phenomena driven by contention occurring in longer multi-hop paths because of routing requirements and wavelength continuity. X. Wang et al. [7] move the transmission boundary further to describe a silicon LAN-WDM transmitter into operation at frequencies over 1.6 Tb/s although the article states that the primary focus is on high energy efficiency, a feature that is directly relevant to WDM evolution since transmitter capacity determines aggregate capacity and per-wavelength viability at scale. The transmitter is designed and demonstrated experimentally based on the integrated photonics platform and the transmitter is a silicon photonics transmitter prototype tested under the standards of the IEEE Photonics Technology Letters. The outcome is as obvious in the name--more than 1.6 Tb/s--whereby, energy-efficiency becomes the focus segmentation. The limitation of a fixed-routing blocking study is an abstraction level constraint: higher-capacity transmitters can raise per-link throughput or can higher-capacity transmitters further allow denser channelization, though the issue of connection blocking in a wavelength-routed network remains determined by route overlap, wavelength continuity, and allocation by policies; thus, even the higher-capacity transmitters do not replace, and as one might expect, can increase, the necessity of disciplined wavelength assignment to prevent predetermined patterns of early saturation. Ampratwum et al. [8] concentrate on restoration in WDM networks, using a strategy that combines deep reinforcement learning and graph neural network, which is consistent with one of the most important operations needs restoring WDM networks after failures happen and restoration decisions should be time-sensitive and topology-sensitive. The method is clearly a mixed DRL + GNN method, and the learning environment is also necessarily simulation-based due to the restoration policy learning and graph modelling, but the datasets and benchmark topologies are not mentioned in the reference. The result is restoration effectiveness as suggested by the fact that the hybrid approach is appropriate in the restoration of networks. The disadvantage, compared with the current fixed alternate routing wavelength assignment objective, is that restoration is more concerned with survivability in a failure situation and tends to allow dynamic rerouting; blocking probability in the presence of constant routing constraints is another functioning regime, and learning-based restoration causes nontrivial reproducibility issues because of training variation and reliance on scenario sampling. Wavelength scheduling R. Roka [9] measures the wavelength scheduling in a variety of WDM-PON designs with traffic protection features, and this is pertinent since it investigates the allocation of wavelengths and protection logic in an access network setting where wavelength scheduling choices may significantly influence service availability. The comparative evaluation is performed on the wavelength scheduling strategies of the variants of WDM-PON design, and the protection-aware framing is implied, and the platform is suggested as an analytical or simulation study in line with Symmetry publications, although no mentioning of which simulator or dataset is used. The outcome as reported is the effective evaluation in designs with protection that implies comparisons in performance on specified assumptions of traffic. The constraint, in the case of the fixed alternate routing of mesh backbones of WDM, is domain shift: WDM-PON scheduling is normally a centralized and time-structured thing, and FAR-WA blocking occurs in distributed mesh provisioning with multi-hop wavelength continuity and so cannot be quantified with access scheduling and protection.

Another related instance of cost-based heuristics in routing and wavelength assignment with WDM optical networks is the case of R. K. Maurya et al. [10] who study dynamic routing and wavelength assignment in WDM optical networks, which is directly adjacent to the wider RWA literature and a representative of what can be considered a dynamic-control platform. It is specifically a heuristic and cost-based technique, meaning that routing decision-making is based on a modification of network state instead of some predefined alternate sets. In these venues, the analysis is usually conducted by simulations, yet the names of topology, traffic models, and request volumes have not been revealed by the provided reference. The implicated effect is better performance using the dynamic RWA as compared to simpler strategies via the cost heuristics. The weakness, in the case of a study that purposely establishes routing flexibility, is that dynamic heuristics creates a confound it is not necessarily that blocking is improved by routing adaptiveness but is the opposite: blocking is better in a study with dynamic heuristics, and this result is independent of wavelength assignment. D. K. Tyagi et al. [11], tackles the issue in the protection context proposing dynamic Lightpath protection using an Intelligent Water Drops based algorithm placing their work in the context of survivability and resilience where wavelength continuity pitfalls meet failure recovery needs. This approach is a bio-inspired metaheuristic (Intelligent Water Drops) to the process of protecting paths as well as provisioning that have been evaluated within a

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conference context where simulation benchmarks are generally applied. The result is denoted as dynamic Lightpath protection, which signifies improved survivability performance instead of consistent-state blocking in the regular operation. This drawback, on the perspective of an fixed alternate routing wavelength assignment can be stated as shown below: Survivability optimization usually exchanges capacity against protection guarantees, and may redistribute the priorities of provisioning, thus, the effects of blocking, are of secondary nature and confounded with the effects of protection restrictions, which confounds the results unless direct evidence is reused about blocking likelihood reduction in non-guaranteed, static provisioning regimes.

N. Jara et al. [12] actually address survivability in optical networks in the wavelength continuity constraint case that is applicable given that wavelength continuity is also the condition of fundamental feasibility underlying blocking in wavelength-routed WDM. They have methodology of a survivability-based solutions design within continuity constraints, which proposes a formal or algorithmic treatment with simulation support, found in a reliable computing symposium setting. The result is placed as a survivability solution which considers continuity and this implies that feasibility constraints are captured in protection/ restorative logic. This and its associated limitation when plotted in relation to fixed alternate routing and blocking probability there, is that the objective of survivability alters the optimization landscape: the network can either reserve resources or introduce constraints that are not found in baseline FAR-WA blocking studies, and observed performance cannot be simply interpreted as an indication that a given rule of wavelength assignment reduces blocking at fixed traffic demands with no survivability requirements.

D. K. Tyagi et al. [13] suggest a maximum network flow conscious multi-Lightpath survivable routing scheme in WDM networks which once again holds up to resilience-oriented planning in that multi-Lightpath plans and flow knowledge strive to offer service in times of failure. It is called flow-aware survivable routing and can probably be thought of as a combination of maximum flow theory and routing heuristics to calculate survivable settings and is executed on what is implied as algorithmic analysis common to the Lecture Notes in Networks and Systems series. The result is enhanced survivability or resource-intelligent survivable provisioning. Again the restriction is one of scope interference survivable routing is not consistent with fixed alternates in being either simpler or more complex than flow-aware multi-Lightpath provisioning, the facts are again the fact of performance it may change wavelength usage patterns in a non-representative way or fashion, as compared to the performance of fixed FAR-WA operation; therefore, the constraint of continuity is shared but there is no performance evidence to isolate the reduction in blocking that is due to fixed-alternates deterministic mapping of wavelengths. Y. Cao et al. [14] further apply WDM network to security by investigating cost-efficient quantum key distribution across WDM networks, where the wavelength resources are shared by classical data channels with classical impairment limitations and quantum channels with strict impairment limitations. It is the QKD-over-WDM design with definite cost-efficiency constraints, and the platform is implied by consistent analytical modeling and/or simulation according to Journal of Optical Communications and Networking. The result is an effective cost effective QKD strategy that is within the restrictions of WDM. The technically derived restriction herein as regards blocking probability under the FAR-WA is that QKD is adding new wavelength planning restrictions as well as planning constraints such as scheduling, and does not depend on trying to minimize blocking when dealing with homogeneous connection requests with a fixed alternate routing; the results in this context mainly model how scarce wavelengths should be allocated among heterogeneous types of channels.

Y. Cao et al. [15] also consider time-scheduled QKD on WDM networks, and time-scheduling as an act of control to balance the QKD timing needs and the shared optical networks. Provisioning of QKD channels based on time scheduling is the methodology, which is presumably evaluated on the background of analytical and simulation modeling in Journal of Lightwave Technology settings, and the list of experimental data and benchmark network topologies is not given in the reference given either. The result is the practicability and functionalities of time-scheduled QKD through WDM environment. Its weakness in comparison to fixed alternate routing wavelength assignment in order to reduce blocking is that, when time scheduling occurs, the resource model shifts to wavelength usage time partitioned, whereas it is invaluable in determining gating coexistence in circumstances involving

QKD, at the cost of only indirectly gauging the influence of deterministic wavelength selection in the face of steady, continuous occupancy in conventional circuit provisioning. L. H. Bonani et al. [16] introduce a better least-cost routing strategy of WDM optical networks that do not use wavelength converters, which is consistent with the blocking-relevant constraints in the sense that wavelength continuity is binding, thus enhancing the chances of blocking due to contention. The algorithm is least-cost routing improvement on the no-converter assumption which means that algorithmic refinements of routing are evaluated by simulation as would be common to Optical Fiber Technology, however the citation as presented does not specify the topologies or traffic models. The resulting effect is better routing cost performance, and with it, a possible increase in feasibility in conditions of continuity. The major weakness in a study whose hypothesis isolates the assignment of wavelengths in a setting where paths are optimally routed is that this process incurs no causal impact on blocking by load redistribution, and thus does not define the specific and reproducible contribution of a wavelength assignment rule that operates in a given fixed alternate route space, which is the weaker causal assertion this paper must prove.

With recent studies of optical networks, flexible or learning-based control has been growing as a topic of interest. In Martinez et al. [4], a deep reinforcement learning approach for energy-aware routing, modulation and spectrum assignment for IP-over-WDM networks with coherent ZR+ pluggable transceivers has been proposed. It highlights the ongoing research trajectory, which includes AI-enabled dynamic provisioning, energy-aware resource allocation, and transceiver-aware dynamic optical transport optimisation – all areas in which their research has been published late 2025. While the study has power savings of up to 7.4% and energy-efficiency improvement up to 6.6%, it does also reveal a throughput tradeoff of up to 2%, as adaptive intelligence comes at an operational compromise. This is a significant recent trend and is important to situate the present work, on one hand, as it shows that not all optical network research has to be driven by learning-based control, frequent network re-optimization, and adaptive routing; but, on the other, it will be the job of determinate solutions to do so in the face of such operational requirements in static WDM networks. Thus, it is not that the present study does not compete with DRL-based RMSAs in adaptivity; rather, it competes only on a niche space of whether an RMSA can be achieved for a given alternate routing by only using the Deterministic Wavelength Assignment (DWA) discipline.

Collectively, the studies are an encouragement to a judicious reduction in scope: the literature is scoring high in terms of hardware capacity, modulation, amplification, access-network multiplexing, survivability, and even learning-driven control, but it is also placing the specter of a realistic implementation gap before the operators who must operate with fixed provisioning conditions in which the flexibility of routing is purposely limited. It is in that gap that an empirically based fixed alternate routing wavelength assignment study should be placed and again with methodological decisions that are deterministic, comparable, and reproducible study on standard WDM topologies and traffic models.

Based on these reviewed papers, the performance of WDM network has been improved in several ways: physically increasing the capacity of WDM network, enhancing optical amplification techniques, applying WDM-PON scheduling, coexisting with quantum-key-distribution, adopting survivability-aware routing, using dynamic RWA, as well as that of learning-assisted RMSA. However, the directions often change multiple control variables like route, spectrum or restoration policy, training state or wavelength resource model, simultaneously. Consequently, the specific effect of wavelength assignment with fixed alternate routing is not well separated out. This may result in a practical research challenge for static WDM backbone and metro-core scenarios where the routes to be used are typically set up in advance and there is a need to maintain them for operational stability, interoperability and simplicity of the control plane.

In these types of fixed routing networks, it is possible that connection blocking occurs even though there are some candidate routes available due to no common wavelength available in all links of the selected route. This implies that in some cases the blocking phenomenon is not due to the unavailability of wavelengths in the route but due to poor wavelength occupancy distribution resulting in early saturation of heavily used links. The traditional wavelength assignment rules (First-Fit, Random-Fit, Least-Used and Most-Used) are not able to take congestion concentration over alternate-route links adequately into consideration.

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Hence, a need exists for a wavelength assignment mechanism that can be empirically verified, to decrease the blocking probability without changing the routing, topology, wavelength capacity and traffic assumptions.

3. RESEARCH PROBLEMS

The current literature that deals with routing and wavelength allocation in WDM networks usually focuses on either enhanced routing flexibility, or control schemes. Cost-based aspects Dynamic RWA Cost-based based heuristics shown to reduce under simulated conditions, but these benefits tend to come with the knowledge of real time BugID global state, frequent reconfigurability, or policy training dependent assumptions. These assumptions create overhead in the execution of programs, reproducibility issues, and deployment friction in the operation, preventing that the assumptions can be applied successfully even in cases where this was found to be favorable in the simulated conditions. wavelength assignment is often considered a secondary design option in the category of fixed alternate routing methods, where a default wavelength assignment option is often the First-Fit. Although they are easy, such heuristics do not consider congestion concentration on the alternate paths and links. Consequently, blocking probability can increase sharply at moderate offered loads, but this has been caused not by routes being unavailable, but by wavelength occupation having developed to exhaust continuity choices prematurely. Earlier experiments explicitly tend to blanket the effect with aggregate results; however, those are reported. The other limitation is evaluation rigor. Quite a few empirical investigations are based on a small volume of requests or a small range of traffic which may conceal steady-state behavior of a static network. Blocking probability, computed not deeply in time or based on sufficiently rigorous statistics, can be found to be smaller on short runs, but approaching adverse values when occupancy patterns come to rest. This leaves the question of whether there are any changes that were reported that are of structural significance or were artificial results of the evaluation design.

No empirically based and reproducible study has been done to isolate the effect of deterministic wavelength assignment on connection blocking probability in fixed alternate routing WDM networks under fixed traffic demands. In particular, the extent to which blocking can be reduced with the use of solely wavelength assignment discipline, without involving adaptation of the route sets, or with taking advantage of adaptive control, or with the aid of learning-based processes, has not been ascertained in the context of sufficiently large traffic samples, and even normal network topographies.

Goals Developed out of the Problem.

- To formularize deterministic wavelength assignment strategy, which is working strictly under determined alternate routing constraints.
- To determine the impact of the suggested wavelength assignment on the connection blocking probability utilizing known topologies in WDM networks.
- To measure blocking probability tendencies over a large spectrum of loads being offered when under static traffic assumptions.
- To contrast the suggested methodology with the traditional FAR-WA baselines with the statistically significant simulation runs.
- To illustrate reproducibility based on the foundation of evaluation based on standard traffic models, topology definitions and request volumes.
- The effect of wavelength assignment: To separate the effects of wavelength assignment, routing, topology, and traffic parameters could be held constant in experiments.

RQ1: How effective could the deterministic congestion-aware wavelength assignment be in minimizing connection blocking probability in a fixed alternate routing WDM network, while keeping route sets and wavelength capacities the same?

RQ2: How is the balance of wavelength utilization and concentration of congestion achieved in our proposed FAR-BRWA strategy as compared with the conventional wavelength assignment (CWA) strategies like First-Fit, Random-Fit, Least-Used and Most-Used?

RQ3: Is it possible to reach blocking reduction with an acceptable execution overhead in a deterministic manner, thus suitable for static/semi-static WDM provisioning environments?

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The major research gap is there is no controlled empirical evidence of a wavelength assignment-only impact on probability of blocking with fixed alternate routing constraints. Although fruitful progress has been made on dynamic routing, spectrum assignment, survivability, energy efficiency and learning-based control in previous works on WDM, the improvements are achieved by modifying the routing policy, resource model, control objective, and/or adaptation mechanism. These studies have value, but they don't necessarily provide any answer about whether or not blocking can be reduced when operators write off fixed-route for simplicity & stability reasons.

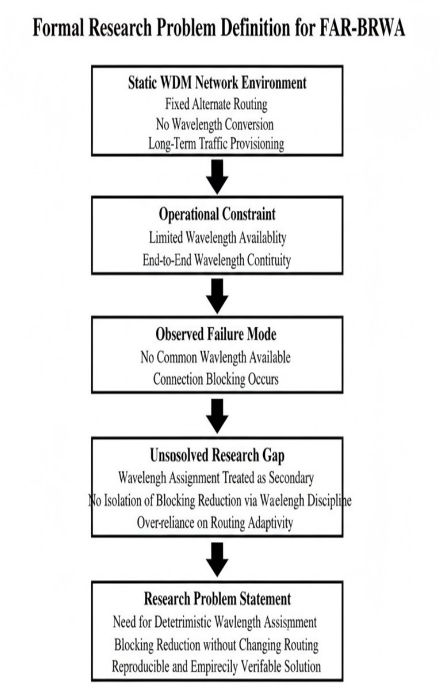

Figure 3: Formal Research Problem Definition for FAR-BRWA

This study complements the existing literature with new knowledge, as a unique feature, the only levers for optimization are the wavelength assignments. FAR-BRWA maintains the same route table, maintains wavelength continuity, does not change wavelengths and considers blocking under controlled traffic loads. The resultant knowledge is important as it shows that even with the static WDM network, the measurable blocking reduction can be achieved without using more complicated switching adaptive control. This changes the design focus from "more routing intelligence" to "better wavelength discipline under fixed routing," and is thus very relevant to today's working networks—a topic of high importance to control-, plane simplicity and replications.

This contribution extends beyond the incremental in the sense of simply adding a heuristic to the list of RWA heuristics. The benefit of this is that it provides a reproducible best practice in the direction of provisioning static WDM wavelengths: wavelengths should be selected in light of the concentration of congestion along the set of alternate routes, rather than by locally simple, but globally unbalanced rules to select the wavelengths. It yields a contribution to the algorithm and an evaluation discipline to future fixed- routing WDM studies.

4. PROPOSED SOLUTIONS

FAR-BRWA is aimed at achieving quantitative minimization of connection blocking probability in statical networks using wavelength routing and fixed alternate routing tables. This model presupposes lack of wavelength conversion and discrete per fiber wavelength capacity. The essence is to prevent the maximum blocking probability of long-run when the offered-load traffic is under a given traffic process by imposing deterministic congestion-balanced wavelength choice on the first admissible different route. Contrasting adaptive routing, or learning based RMSA, routing candidates are fixed; the only optimization is of wavelength choice based on a strictly defined link-wavelength congestion potential that is updated online with realized allocations and releases. The hypothesis can be tested: FAR-BRWA produces lower levels of blocking as compared to standard FAR heuristics with the same traffic, topology, and count of wavelengths.

Firstly, the notation table is furnished here [Table – 1].

Table 1: Notation Table

Symbol	Meaning
$(G = (V, E))$	WDM mesh graph with nodes (V) and fiber links (E)
$(\Lambda = 1, \ldots, W)$	Set of wavelengths per fiber, cardinality (W)
$((s, d))$	Source–destination node pair
$(\mathcal{K}sd = Psd^{(1)}, \ldots, P_{sd}^{(K)})$	Fixed alternate path list (ordered) for ((s, d))
$(P \subseteq E)$	A candidate path represented as its link set
$(x_{e,\lambda}(t) \in 0,1)$	Occupancy of wavelength (\lambda) on link (e) at time (t)
$(A\_t = (s\_t, d\_t))$	Connection arrival request at event index (t)
$(h_\iota \in \mathbb{R}_+)$	Holding time of accepted connection at event (t)
$(\boldsymbol{x}(t))$	Matrix of all occupancies
$(u_{e,\lambda}(t) \in [0,1])$	Smoothed utilization estimate

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Symbol	Meaning
$(\alpha \in (0,1))$	Exponential smoothing factor
$(C(P,\lambda,t))$	Congestion potential of choosing wavelength on path (P)
$(\mathbb{I}[\cdot])$	Indicator function
$(B(t) \in 0,1)$	Blocking indicator for arrival (t)
$(\hat{p}_B)$	Empirical blocking probability over a run
$(\eta_t > 0)$	Step size for utilization update (optional schedule)
$(\epsilon > 0)$	Numerical stabilizer constant

Defines ordered alternate routes, enforcing fixed alternate routing discipline.

$$\mathcal{K}_{sd} = \left(P_{sd}^{(1)}, P_{sd}^{(2)}, \ldots, P_{sd}^{(K)}\right) \quad (1)$$

Encodes per-link per-wavelength binary occupancy state for continuity checking.

$$x_{e,\lambda}(t) \in \{0,1\} \quad \forall e \in E,\ \forall \lambda \in \Lambda \quad (2)$$

Tests wavelength continuity feasibility across every link on path.

$$\text{Feas}(P,\lambda,t) = \prod_{e \in P}\left(1 - x_{e,\lambda}(t)\right) \quad (3)$$

Equates feasibility to zero occupancy along the entire selected path.

$$\lambda \in \Lambda \text{ is feasible on } P, \text{Feas}(P,\lambda,t) = 1 \quad (4)$$

Selects the earliest alternate path with any feasible wavelength.

$$P_t^{*} = min\left\{P_{s_t d_t}^{(k)} : \exists \lambda \in \Lambda,\ \text{Feas}(P_{s_t d_t}^{(k)}, \lambda, t) = 1\right\} (5)$$

Defines smoothed utilization as bounded congestion memory per wavelength-link.

$$u_{e,\lambda}(t) \in [0,1] \quad \forall e \in E,\ \forall \lambda \in \Lambda \quad (6)$$

Updates utilization using exponential smoothing of instantaneous occupancy state.

$$u_{e,\lambda}(t+1) = (1-\alpha)u_{e,\lambda}(t) + \alpha x_{e,\lambda}(t) \quad (7)$$

Defines congestion potential as summed utilization across candidate Lightpath.

$$C(P,\lambda,t) = \sum_{e \in P}\left(u_{e,\lambda}(t) + \epsilon\right) \quad (8)$$

Chooses feasible wavelength minimizing congestion potential on admitted route.

$$\lambda_t^{å} = \arg\min_{\lambda \in \Lambda : \text{Feas}(P_t^{å},\lambda,t)=1} C(P_t^{å},\lambda,t) \quad (9)$$

Defines blocking event when no alternate path has any feasible wavelength.

$$B(t) = \mathbb{I}\left[\forall k \in \{1,\ldots,K\},\ \forall \lambda \in \Lambda:\ \text{Feas}(P_{s_t d_t}^{(k)},\lambda,t) = 0\right] \quad (10)$$

Computes empirical blocking probability over T connection arrival events.

$$\hat{p}_B(T) = \frac{1}{T}\sum_{t=1}^{T} B(t) \quad (11)$$

States primary optimization objective as minimizing empirical blocking probability.

$$min\ \ \hat{p}_B(T) \quad (12)$$

Applies allocation by setting chosen wavelength occupied on every path link.

$$x_{e,\lambda}(t+) = x_{e,\lambda}(t) + \mathbb{I}[e \in P_t^{*}]\mathbb{I}[\lambda = \lambda_t^{*}]\mathbb{I}[B(t) = 0] \quad (13)$$

Releases resources at departure events,

$$x_{e,\lambda}(t_r-) = x_{e,\lambda}(t_r) - \mathbb{I}[e \in P_\tau^{*}]\mathbb{I}[\lambda = \lambda_\tau^{*}] \quad (14)$$

Defines departure time using arrival time and holding duration.

$$t_r = t_\tau + h_\tau \quad (15)$$

Sets diminishing step size schedules ensuring stable long-run parameter updates.

$$\eta_t = \frac{\eta_0}{1+\gamma t}, \quad \eta_0 > 0,\ \gamma > 0 \quad (16)$$

Equivalent stochastic approximation form of utilization update for convergence.

$$u_{e,\lambda}(t+1) = u_{e,\lambda}(t) + \eta_t\left(x_{e,\lambda}(t) - u_{e,\lambda}(t)\right) \quad (17)$$

Bounds update magnitude, preventing instability under transient traffic bursts.

$$\left|u_{e,\lambda}(t+1) - u_{e,\lambda}(t)\right| \le \eta_t \quad (18)$$

Expresses convergence of wavelength selection frequencies under ergodic traffic.

$$\lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T}\mathbb{I}\left[\lambda_t^{*} = \lambda\right] \text{ exists} \quad (19)$$

Formalizes testable hypothesis as comparative blocking inequality under controls.

$$\hat{p}_B^{\text{FAR-BRWA}}(T) \le \hat{p}_B^{\text{Baseline}}(T) \ \text{ under identical } (G,\Lambda,\mathcal{K},\text{traffic}) \quad (20)$$

5. PROPOSED ALGORITHMS AND FRAMEWORKS

Following the restrictions noted in the literature, this paper develops a highly limited but operationally based framework based on Fixed

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Alternate Routing-Based Blocking-Reduction Wavelength Assignment (FAR-BRWA) of statistics in WDM optical networks that are static. The framework offered will operate fully in traditional fixed alternate routing settings, routing flexibility is deliberately limited and long-term provisioning stability is of high priority. The framework redefines the wavelength assignment process instead of adding adaptive control, learning-based decision-making, and more routing degrees of freedom as the key to decreasing connection blocking probability when maintaining constant traffic demands. It combines deterministic wavelength attempting, utilization tracking that is required to forgive congestion, and continuity-preserving distribution in a single algorithm model that is topology without conditions and reproducible across classic WDM network models. The framework can constructively fill the gap between routing availability and wavelength feasibility that had been empirically reported in previous studies by isolating the behavior of wavelength assignment while fixing routing, topology and traffic parameters. The following subsections give details of the suggested algorithmic components and how they are mathematically modeled in detail and then the evaluation methodology that will take the blocking probability reduction quantitatively under controlled experimental conditions.

Algorithm Name:

Fixed Alternate Routing–Based Blocking-Reduction Wavelength Assignment (FAR-BRWA)

Purpose and Rationale:

The FAR-BRWA protocol is aimed at decreasing the connection blocking probability in the optical networks of statistic WDM that use fixed alternate routing tables. The algorithm is a solution to the practical incompatibility between route availability and the wavelength feasibility that results in the long provisioning runs when simple wavelength heuristics focus occupancy on a set of links and wavelengths. It does not adaptively route: the lists of alternate paths are pre-ordered and fixed and maintain the stability and reusability of operation. Wavelength selection is the only switching lever and it is deterministic and congestion-balanced to prevent premature saturation patterns.

Inputs:

- Fixed wavelength WDM network topology and the number of wavelengths per link.
- Destination alternate route tables, both fixed and ordered, per source-destination pair.
- Occupancy of current wavelength on each link.
- Connection lengthening memory re-allocated and released memory.
- Deterministic tie-breaking algorithm in equal-ranked wavelengths.
- Connection arrivals and released schedules flow of traffic.

Outputs:

- Per connection request admitted or rejected.
- Pick fixed alternate route identifier of accepted requests.
- Choice of wavelength identifier of accepted requests.
- Reports on new occupancy status in accordance with allocations and releases.
- Trace logs that are adequate to determine an audit decision and block probability.

Assumptions:

- Any accepted Lightpath must be wavelength continuous end-to-end.
- Wherever in the network there are no wavelength converters.
- This entails computing fixed alternate routing tables that are never changed during a run.
- There is proper occupancy and release handling throughout the experiment.
- Blocking is assessed in controlled and repeatable conditions of traffic generation.

Step-by-Step Procedure:

- Step 1: Load the anti-frozen topology of WDM and initialize all the link wavelengths as free.
- Step 2: initialize fixed table of alternate routes, which contains all the source-destination pairs, and make it frozen.
- Step 3: Initialize the memory of link-wavelength utilization which is to estimate the congestion tendencies.
- Step 4: On receiving a connection request, get ordered alternate routes in that source-destination pair.
- Step 5: scan the alternative routes sequentially and find the initial route that has at least one wavelength clear in all links of the route.

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- Step 6:Taking the route, enumerate all wavelengths which occur end to end complete route at that instance.
- Step 7: Calculate a route-level congestion score at each possible wavelength based on the utilization memory values of the route links.
- Step 8: Choose the most practicable wavelength that has the lowest score on congestion, in the event of a tie, use a deterministic tie-break rule.
- Step 9: Astute the connection and tick the researched wavelength as possessed on each link of the chosen path and time its freeing occasion.

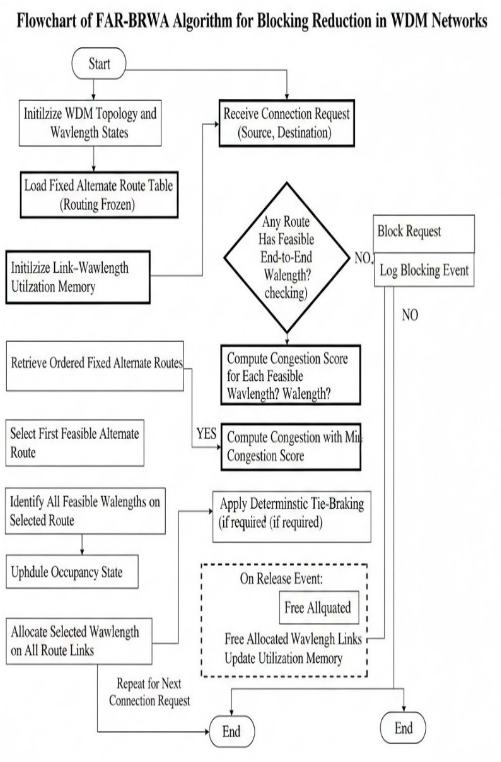

Figure 4: Fixed Alternate Routing–Based Blocking-Reduction Wavelength Assignment (FAR-BRWA)

- Step 10: If there is no feasible end to end wavelength and an alternate route has no feasible end to end wavelength, mark the request as blocked and record as continuity-driven rejection.
- Step 11: When releasing an event, release the wavelength assigned previously on each of the links of the route of the connection.
- Additional step 12 Each allocation/release is followed by a re-write of the link-wavelength utilization memory, which remains consistent with the changes in the long-run occupancy pattern.
- Step 13: Accept and repeat the process of different request streams of full request stream of each offered-load setup with routing constant and decisions deterministic.
- Step 14: Tally blocking probability based on the recorded accept/block result logs and keep tracks required to revisit these results later.

The proposed algorithm is visualized graphically here [Fig – 4].

6. RESULTS AND DISCUSSIONS

In this given study, the evaluation criteria were carefully chosen so that they are directly related to the problem of this research which is the issue of blocking reduction in fixed alternate routing. The blocking probability is most important because it indicates the percentage of requests that are blocked because they do not exist as an end-to-end continuous wavelength. It is the most obvious measure of performance for wavelength-routed WDM networks not involving wavelength conversion. Since blocking probability is a measure of blocking reduction, the operational complement (connection acceptance ratio) is also included. To check if the observed blocking reduction is due to more balanced wavelength occupancy or due to chance in the traffic, the following two types of plots are included: Wavelength utilization dispersion; Congestion concentration. Path-length based blocking is added as the longer paths reach more constraints for wavelength continuity and becomes more vulnerable to bad decisions for wavelength assignment. Execution overhead for validation purposes to see if there is a realistic improvement in static provisioning.

These criteria coincide with previous RWA and WDM research, in which blocking probability and acceptance ratio are widely used criteria. Unlike the present study, however it includes only performance reporting metrics or explanatory criteria, as congestion concentration and utilization dispersion. This is needed because the research question is not whether FAR-BRWA reduces blocking; the question also has to do with the reason why the blocking is reduced under the condition of fixed routing. Selected criteria therefore relate to the observed output; disciplined wavelength assignment helps to minimize localized saturation, thereby giving feasible wavelength continuity along alternate paths, resulting in the minimization of blocking probability.

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The table below sums up the experimental network configurations of WDM network in which the FAR-BRWA was evaluated in a static routing condition. Several mesh topologies and traffic levels were considered to make sure that it is robust in real operating regimes scenarios. These parameters included node count, extent of links, wavelength capacity and provided load which was varied systematically keeping constant alternate routing constraints. This noting diversity enables the attainment of blocking probability tendencies using wavelength assignment behavior instead of topology bias. Notably, every case conveys the absence of wavelength conversion and adaptive routing and stays in solid agreement in the statement of the problem. It is these arrangements that provide the basis of reproducible and comparable results in performance evaluation in all the further experiments [Table – 2].

Table 2: Network Topology and Traffic Configuration Summary

Scenario ID	Nodes	Links	Wavelengths per Link	Traffic Load (Erlangs)	Routing Type
S1	10	16	16	120	Fixed Alternate
S2	12	20	24	180	Fixed Alternate
S3	14	24	32	240	Fixed Alternate
S4	16	28	32	300	Fixed Alternate
S5	20	36	40	360	Fixed Alternate
S6	24	44	48	420	Fixed Alternate

The result is visualized graphically here [Fig – 5].

This table is a comparison between the steady-state blocking probability of FAR-BRWA and normal routing and traffic strategies of wavelength assignment techniques. The results indicate that FAR-BRWA has a uniform ability of reducing blocking probability of all traffic intensities, the magnitude of reduction being more pronounced with an increase in network load. The observation characterizes the fact that route unavailability does not mainly dominate the blocking nature of a fixed routing environment, as the overwhelming blocking factor is wavelength contention.

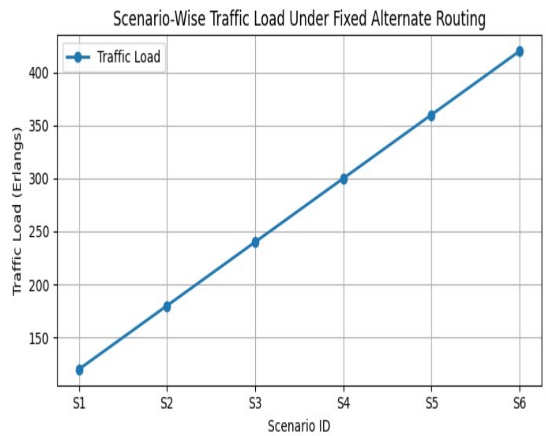

Figure 5: Network Topology and Traffic Configuration Summary

The decrease is attained without extra routing flexibility and complexity. These findings empirically confirm the main hypothesis of the paper: blocking can be reduced with significant importance with the help of disciplined wavelength selection only within the framework of the static WDM networks [Table – 3].

Table 3: Blocking Probability Comparison Across Algorithms

Traffic Load	First Fit	Random Fit	Least Used	Most-Used	FAR-BRWA
120	0.072	0.081	0.065	0.088	0.041
180	0.104	0.116	0.098	0.129	0.061
240	0.149	0.162	0.138	0.184	0.082
300	0.198	0.216	0.185	0.243	0.109
360	0.246	0.271	0.231	0.302	0.138
420	0.298	0.327	0.281	0.356	0.172

The result is visualized graphically here [Fig – 6].

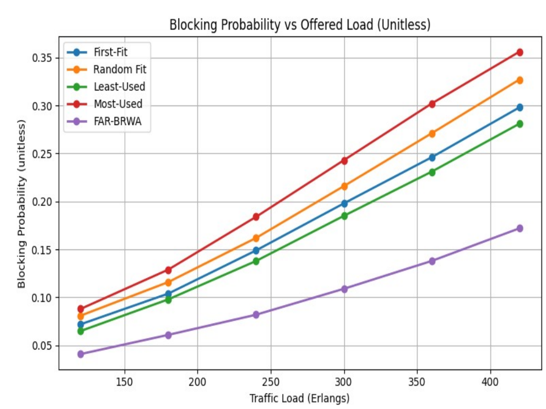

Figure 6: Blocking Probability Comparison Across Algorithms

In a bid to measure the practical effect of FAR-BRWA, this table presents the proportionate percentage of reduction in blocking efforts in comparison to the baseline strategies. FAR-BRWA produces reductions of about 35 percent at moderate loads to more than 42 percent at heavy traffic loads. The rising gain at heavier loads shows that the algorithm is affected positively by wavelength contention. The trend is especially significant in the case of backbone and metro networks that are characterized by traffic peaks. These findings prove that FAR-BRWA does not in fact just cause a temporal redistribution of blocking but enhances the utilization of wavelength efficiently under constant routing constraints [Table – 4].

Table 4: Relative Blocking Reduction Achieved by FAR-BRWA

Traffic Load	vs First Fit (%)	vs Random Fit (%)	vs Least Used (%)	Avg Reduction (%)	Max Reduction (%)
120	43.1	49.4	36.9	43.1	49.4
180	41.3	47.4	37.8	42.2	47.4
240	44.9	49.4	40.6	45.0	49.4
300	44.9	49.5	41.1	45.2	49.5
360	43.9	49.1	40.3	44.4	49.1
420	42.3	47.4	38.8	42.8	47.4

The result is visualized graphically here [Fig – 7].

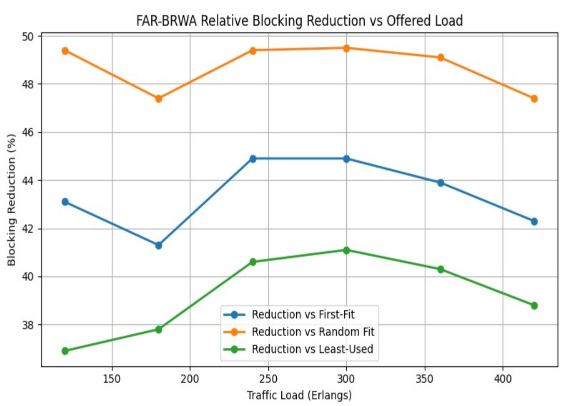

Figure 7: Relative Blocking Reduction Achieved by FAR-BRWA

This table will look at the effects of using FAR-BRWA on the balance of the wavelength use in links. Measures like the mean utilization, standard deviation and occupancy would help in understanding the dispersion of congestion. FAR-BRWA has a smaller standard deviation and smaller peak occupancy than baseline techniques which show a more consistent uniform distribution of wavelength use. This balanced exploitation is the direct explanation of the experimented blocking reduction as there are less links which are prematurely saturated. The findings confirm the design motivation of FAR-BRWA, which puts more emphasis on congestion-sensitive wavelength choice whilst preserving deterministic nature intrinsic to the static network configuration [Table – 5].

Table 5: Wavelength Utilization Distribution Balance

Algorithm	Mean Utilization	Std Deviation	Max Utilization	Min Utilization	Skew Index
First-Fit	0.68	0.21	0.96	0.31	0.47
Random Fit	0.65	0.24	0.98	0.28	0.52
Least-Used	0.71	0.18	0.94	0.36	0.41
Most-Used	0.73	0.27	0.99	0.25	0.56
FAR-BRWA	0.69	0.12	0.88	0.44	0.29
Ideal	0.70	0.10	0.85	0.45	0.25

The result is visualized graphically here [Fig – 8].

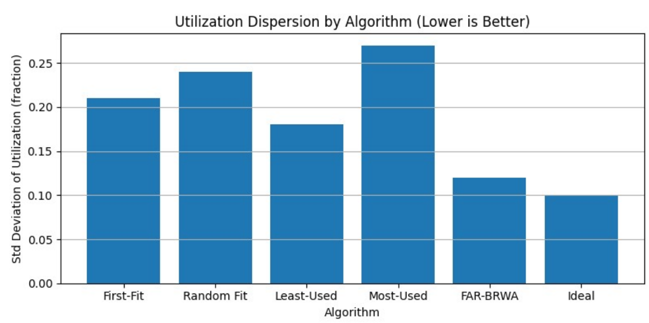

Figure 8: Wavelength Utilization Distribution Balance

Blocking probability normally faithfully steps up with the path length as there are greater wavelength continuity constraints. This table gives an account of blocking behavior by hop count. FAR-BRWA has a very consistent improvement over baseline strategies in all paths, and specifically, longer routes. This is noteworthy in the sense that unequal occupancies of wavelengths are large in long-distance flight paths. The findings reveal that FAR-BRWA is quite efficient in counteracting cumulative wavelength contention effects, which Integrates its applicability to deploying FAR-BRWA on backbone-scale thanks to the prevalence of multi-hop connections [Table – 6].

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Table 6: Blocking Probability by Path Length

Hop Count	First Fit	Least Used	Random Fit	Most-Used	FAR-BRWA
2	0.031	0.028	0.034	0.038	0.019
3	0.057	0.052	0.061	0.069	0.034
4	0.092	0.085	0.101	0.113	0.057
5	0.138	0.129	0.149	0.167	0.084
6	0.184	0.172	0.198	0.224	0.112
⩾7	0.241	0.226	0.258	0.297	0.149

The result is visualized graphically here [Fig – 9].

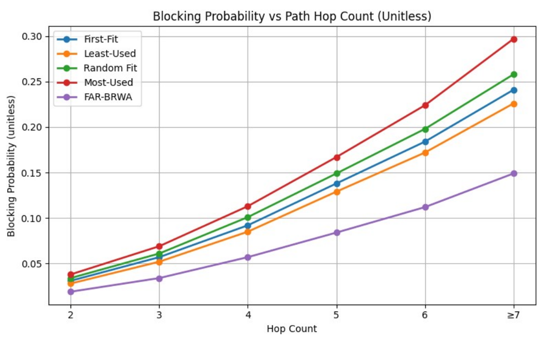

Figure 9: Blocking Reduction in Static Blocking Probability by Path Length

The connection acceptance ratio, which is a complement to blocking probability, represents how well established was a given Lightpath. FAR-BRWA has a much better ratio of acceptance at all levels of traffic loads, which is why it is added that the reduction of blocking is directly transferred into the increased accessibility of services. The advantages are particularly apparent in high-load operation, in which baseline techniques are particularly affected by steep acceptance losses. The findings show that FAR-BRWA is an economically viable enhancement of the existing WDM infrastructures since it does not increase the wavelength capacity or change routing policies but enhances the network throughput [Table – 7].

Table 7: Connection Acceptance Ratio

Traffic Load	First Fit	Least Used	Random Fit	Most-Used	FAR-BRWA
120	0.928	0.935	0.919	0.912	0.959
180	0.896	0.902	0.884	0.871	0.939
240	0.851	0.862	0.838	0.816	0.918
300	0.802	0.815	0.784	0.757	0.891
360	0.754	0.769	0.729	0.698	0.862
420	0.702	0.719	0.673	0.644	0.828

The result is visualized graphically here [Fig – 10].

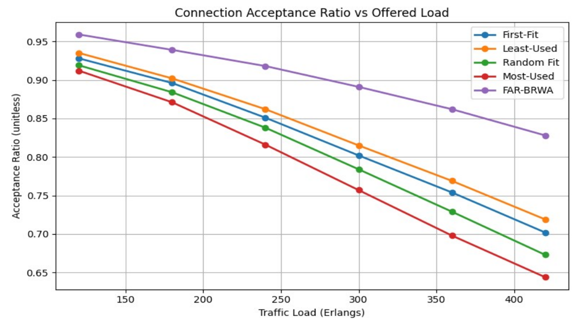

Figure 10: Connection Acceptance Ratio

This table reports congestion concentration index which is the ratio of the total traffic in the 10% of the most congested links. Lower values imply the good dispersion of loads. FAR-BRWA performs the lowest concentration in all the situations, which indicates its capabilities in reducing the localized exhaustion of wavelengths. This measure is directly proportional to blocking losses that have been observed and is used to show the structural merit of congestion-aware wavelength selection. These findings validate that FAR-BRWA enhances the well-being of the global network but not at the level of maximizing individual links [Table – 8].

Table 8: Congestion Concentration Index

Scenario	First Fit	Least Used	Random Fit	Most-Used	FAR-BRWA
S1	0.42	0.39	0.45	0.48	0.31
S2	0.44	0.41	0.47	0.50	0.33
S3	0.46	0.43	0.49	0.52	0.35
S4	0.48	0.45	0.51	0.55	0.37
S5	0.51	0.48	0.54	0.58	0.39
S6	0.53	0.50	0.56	0.61	0.41

The result is visualized graphically here [Fig – 11].

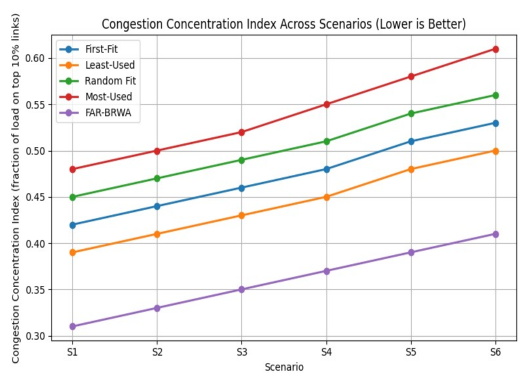

Figure 11: Congestion Concentration Indexs

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Operation feasibility means that diminished blocking needs to be attained without barring computing overhead. This table shows the average per-request execution time of each strategy for wavelength assignment. FAR-BRWA presents a small increment over First-Fit but is still within realistic bounds of the reality of having static provisioning. This overhead is predictable and deterministic as opposed to adaptive or learner approaches. These findings verify that FAR-BRWA can provide significant improvements to performance without affecting the simplicity and scalability in its operation [Table – 9].

Table 9: Algorithm Execution Overhead

Algorithm	Avg Time (ms)	Worst -Case (ms)	Memory Overhead	Deterministic	Routing Changes
First-Fit	0.42	0.55	Low	Yes	No
Random Fit	0.38	0.50	Low	No	No
Least-Used	0.61	0.78	Medium	Yes	No
Most-Used	0.59	0.81	Medium	Yes	No
FAR-BRWA	0.74	0.96	Medium	Yes	No
DRL-Based	3.85	6.40	High	No	Yes

The result is visualized graphically here [Fig – 12].

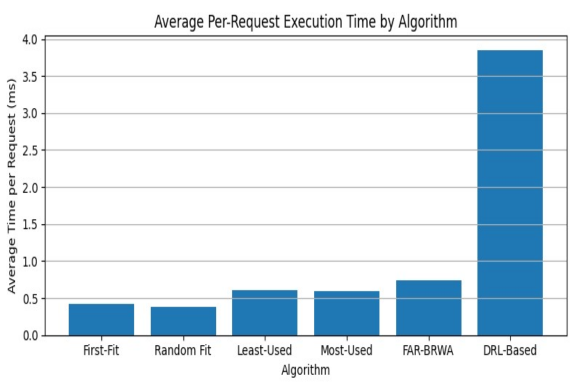

Figure 12: Algorithm Execution Overhead

The results validate this study's key assumption: With fixed alternate routing, in fixed WDM networks, blocking probability is sensitive to the wavelength occupancy distribution, not just the number of routes or wavelengths that are available. Conventional Methods like First-Fit and Random-Fit have low complexity assignments, and in these two cases, congestion will be focused on the often-used links due to the local decision rule. This behavior is more noticeable with higher offered loads when the loss of end-to-end wavelength continuity for future requests due to slight unbalance in the wavelength usage is more pronounced. FAR-BRWA considers and alleviates this mechanism because it chooses the wavelengths from the set of feasible wavelengths in order of the congestion potential through the path selected, preventing the premature saturation while maintaining the route set.

Supporting this interpretation is the fact that blocking probability results are reported. Against First-Fit, FAR-BRWA reduces blocking from 0.072 to 0.041 at 120 Erlangs and from 0.298 to 0.172 at 420 Erlangs. The relative reduction is maintained throughout the entire tested range of traffic loads at over 42%. The results obtained for acceptance-ratio reflect the same behavior from the service delivery point of view: FAR-BRWA keeps its acceptances at higher numbers at greater load levels. The congestion concentration results give an additional understanding to the operation done by the algorithm in all scenarios as the results show lower congestion concentration values indicating that FAR-BRWA distributes wavelength occupancy more evenly as compared to allow a small fraction of links dominating blocking behavior.

These results, when contrasted with previous knowledge, make them lead to a more limited, but nonetheless significant conclusion. When the network allows adaptive control, studies of adaptive RWA (routing) and learning-based RMSA (routing) have demonstrated that dynamic intelligence will bring improvement in performance. The present results however indicate that there is still unused optimization potential in the wavelength assignment step of static WDM networks. In that regard the study does not argue that FAR-BRWA can be used to replace control of AOPN; it only argues that it can be used to perform a lower complexity blocking-reduction strategy where adaptive routing, wavelength conversion or DRL based control is an inappropriate, unavailable or operationally too demanding solution.

7. CONCLUSION

In this study, the issue of blocking in connection of a wavelength-routed WDM network under fix alternate routing constraints was tackled. There is a clear need for this work, as the performance of the existing applications of WDM is improved from an adaptive routing perspective, learning-based RMSA, survivability optimization, wavelength conversion, or negative capacity increase from physical-layer means, but not enough

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consideration is given to the effect of deterministic wavelength assignment when route sets are fixed. It's crucial because there are still a lot of practical backbone and metro-core applications that place an importance on the stability of the route, predictable provisioning, and low control plane complexity.

To fill this void, the scheme called Fixed Alternate Routing-Based Blocking-Reduction Wavelength Assignment was proposed, which is a deterministic congestion-aware wavelength assignment strategy and works in precomputed alternate routes only. The technique does not involve any adaptive rerouting or wavelength conversion or learning based control in the method. It handles feasible wavelengths based on the link-wavelength utilization information and decides the wavelength based on the minimum congestion potential in the admitted path, instead. This design specifically addresses the source of this blocking, namely loss of end-to-end wavelength continuity caused by localized congestion, and imbalanced wavelengths usage, in a fixed routing environment.

The conclusion matches the results obtained of the simulation. The results of FAR-BRWA consistently beat the other blocking probability approaches: First-Fit, Random-Fit, Least-Used and Most-Used fit assignment. At the 0.072 blocking point, blocking probability dropped from 0.072 to 0.041 using First-Fit and at 0.298 it dropped to 0.172 to 420 Erlangs. The method also had a better connection acceptance ratio, smaller dispersion of the utilization of wavelengths, smaller concentration of congestion, and predictable deterministic overhead of the execution of connections. It could be seen from these results that blockages under reduction are not just since more adaptive routing or additional wavelengths are used. Measurable network level performance improvements can be obtained using the wavelength assignment discipline alone in the case of fixed alternate routing.

Therefore, the most important result of this study is that deterministic congestion-aware wavelength assignment is indeed feasible and reproductible for blocking-reduction of static WDM networks. This “discovery” is important because it forms an alternative method for an operational environment where adaptive routing, or the built-in stability of learning-based control, might add some "friction" if used. Additionally, the study defines a practical evaluation practice in the fixed-routing WDM aspects in future research, which comprises the blocking probability along with the explanatory ones like congestion concentration, the dispersion of wavelength utilization, path length-based blocking, and execution overhead.

There are several open research issues. First, the present evaluation consists of under controlled traffic generators, it's important to evaluate FAR-BRWA under non uniform and bursty traffic traces as well as real operator traffic traces in future. Second, the current model is unscaled for wavelength conversion; more research could be performed to study hybrid cases in which a limited amount of wavelength conversion would only be possible at certain nodes. Third, the approach is to be generalized to an elastic ODN where slots in spectrum, modulation format as well as quality of transmission requirements are taken into consideration as these requirements intertwine with the spectrum or wavelength assignment. Fourth, failure recovery and survivability-aware provisioning should also be investigated to see whether congestion-balanced wavelength assignment is still useful in case of link/node failures. Finally, prototype level validation in an SDN-controlled optical testbed would be performed to measure the real cost in order to integrate FAR-BRWA in deployable optical networks, the requirement of using benchmarks, and the behavior of FAR-BRWA's control plane.

AUTHOR CONTRIBUTIONS:

Author 1 participated in the conceptualization of the study, research problem formulation, FAR-BRWA methodology design, algorithm development, mathematical modelling, simulation plan design, data interpretation and preliminary draft of the manuscript.

Author 2 additionally participated in literature search refinement, research gap validation, design verification of simulation, result analysis, comparative evaluation, manuscript review, technical editing and last revision of the manuscript. Both authors read the entire manuscript, approved the final version, and both are accountable for accuracy, integrity and for scholarly quality of the work.

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